Tracking and forecasting community responses to climate perturbations in the California Current Ecosystem

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Supporting Information

S1 Appendix: Standardization of time series from spatially resolved datasets.

Datasets collected through the Rockfish Recruitment and Ecosystem Assessment Survey (RREAS; pelagic juvenile fish and invertebrates survey) and the California Cooperative Oceanic Fisheries Investigations (CalCOFI, ichthyoplankton survey) include spatial attributes and were standardized using Generalized Additive Models (GAM) to create a univariate time series for each species included in our analysis.

RREAS Survey

Because many species in the RREAS survey were absent from a large number of observed trawls, we modeled species occurrence and abundance separately, using a delta GAM approach with two sub-models (Hastie 1990, Guissan 2002). In the first sub-model, species occurrence (presence-absence) was modelled using a binomial GAM with a logit link. In the second model ('positive model'), species abundance (count) conditional on the catch of at least one individual was modelled using a Poisson GAM with a log link. The formulations of the two sub-models were analogous and as follows:

$$P_{yr(\varphi,\lambda)} \text{ or } C_{yr(\varphi,\lambda)} = yr + s(\varphi,\lambda) + jday_{yr(\varphi,\lambda)} + jday^2_{yr(\varphi,\lambda)} + \varepsilon_{yr(\varphi,\lambda)}$$

where P, the probability of species occurrence, or C, an estimate of species abundance when the species is present, is a function of year (*yr,* as factor), latitude (φ) and longitude (λ), and Julian day (*jday*). A two-dimensional smoothing function is denoted by s and ε indicates an error term.

Using the fitted GAMs for each species, we generated predictions of overall abundance of individual species. First, we created spatial occurrence and abundance distribution profiles by creating a grid of all combinations of model explanatory variables: geographic coordinates (latitude and longitude), Julian day, and year. We restricted the range of geographic coordinates to 20 values within the upper 0.8 and lower 0.2 quantiles of the data set, and bounded the range of Julian days to the upper 0.9 and lower 0.1 quantiles. This was done to avoid edge effects that can result in unrealistic predictions. All unique sampling years were included in the grid. Next, the probability of occurrence and estimates of abundance were predicted for each combination of the explanatory variables, and then the predictions from the two sub-models were multiplied to determine the overall abundance of individual species. Lastly, we calculated the mean standardized abundance of each species in each year from the prediction grid to generate the univariate time series of species abundance used in our study analyses.

CalCOFI survey

The CalCOFI time series of ichthyoplankton densities were standardized using a Tweedie GAM (power parameter fixed at 1.25) (Tweedie 1984, Dunn ad Smyth 2002). The model formulation was as follows:

$$D_{yr(\varphi,\lambda)} = yr + season + s(\varphi,\lambda) \cdot yr + \varepsilon_{yr(\varphi,\lambda)}$$

where species density (D) is a function of year (yr), season (spring, summer), and latitude (φ) and longitude (λ). The two-dimensional smoothing function and error term are indicated by s and ε, respectively.

Similar to above, we used the fitted GAMs for each species to generate predictions of species densities. We first created a spatial abundance distribution profile by creating a grid of different combinations of the model covariates. Here we restricted the range of geographic coordinates (latitude and longitude) to those from sampling stations that were sampled ≥ 20 years. We included all sampling years in the grid and limited the season to spring only. Species densities were then predicted for each combination of the model covariates, and the univariate time series of species abundance was generated by calculating the mean standardized density of each species in each year from the prediction grid.

The delta GAMs and Tweedie GAMs were run using the 'mgcv' package (v1.8-34; Wood 2011, 2017) in R.

References

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S1 Table: A list of climate and biology time series included in the analyses and the associated units of measurements, data transformations (if applicable), years of data, and data sources.

Variable	Metric	Years	Source
Climate			
Sea surface temperature, ˚C	July-June mean, 31-34.5 and 34.5-40.5˚N, coast to 100 km offshore	1980-2018	1
Sea surface height, m	July-June mean, 31-34.5 and 34.5-40.5˚N, coast to 100 km offshore	1980-2018	1
Isothermal Layer Depth, m	July-June mean, 31-34.5 and 34.5-40.5˚N, coast to 100 km offshore	1980-2018	1
Brunt-Väisälä Frequency, s^{-1} (stratificatoin)	July-June mean, 31-34.5 and 34.5-40.5˚N, coast to 100 km offshore	1980-2018	1
CUTI, m^2 s^{-1} (upwelling)	July-June mean, 31-34.5 and 34.5-40.5˚N, coast to 75 km offshore	1980-2018	1
BEUTI, mmol s^{-1} m^{-1} (nitrate flux)	July-June mean, 31-34.5 and 34.5-40.5˚N, coast to 75 km offshore	1980-2018	1
Biology			
Zalophus californianus pup births (California sea lion)	Annual mean live pup count, San Miguel, CA, log-tranformed	1997-2018	2
Zalophus californianus pup weight	Annual mean femlae pup weight, San Miguel, CA, log-tranformed	1997-2018	2
Zalophus californianus pup growth rate	Annual mean, female pup growth rate, San Miguel, CA	1997-2018	2
Oceanodroma homochroa (ashy storm-petrel)	Standardized seabird productivity anomaly, SE Farallon Island	1971-2018	3
Phalacrocorax penicillatus (Brandt's cormorant)	Standardized seabird productivity anomaly, SE Farallon Island	1971-2018	3
Ptychoramphus aleuticus (Cassin's auklet)	Standardized seabird productivity anomaly, SE Farallon Island	1971-2018	3
Uria aalge (common murre)	Standardized seabird productivity anomaly, SE Farallon Island	1972-2018	3
Phalacrocorax pelagicus (pelagic cormorant)	Standardized seabird productivity anomaly, SE Farallon Island	1971-2018	3
Cepphus columba (pigeon guillemot)	Standardized seabird productivity anomaly, SE Farallon Island	1971-2016	3
Cerorhinca monocerata (rhinocerus auklet)	Standardized seabird productivity anomaly, SE Farallon Island	1986-2018	3
Larus occidentalis (western gull)	Standardized seabird productivity anomaly, SE Farallon Island	1971-2018	3
Bathylagoides wesethi (snubnose blacksmelt)	Standardized spring ichthyoplankton density, log-transformed	1951-2018	4
Bathylagus pacificus (slender blacksmelt)	Standardized spring ichthyoplankton density, log-transformed	1951-2018	4
Ceratoscopelus townsendi (Dogtooth lampfish)	Standardized spring ichthyoplankton density, log-transformed	1951-2018	4
Engraulis mordax (northern anchovy)	Standardized spring ichthyoplankton density, log-transformed	1951-2018	4
Leuroglossus stilbius (California smoothtongue)	Standardized spring ichthyoplankton density, log-transformed	1951-2018	4
Lipolagus ochotensis (eared blacksmelt)	Standardized spring ichthyoplankton density, log-transformed	1951-2018	4
Merluccius productus (Pacific hake)	Standardized spring ichthyoplankton density, log-transformed	1951-2018	4
Protomyctophum crockeri (California flashlightfish)	Standardized spring ichthyoplankton density, log-transformed	1951-2018	4
Sardinops sagax (Pacific sardine)	Standardized spring ichthyoplankton density, log-transformed	1951-2018	4
Stenobrachius leucopsarus (northern lampfish)	Standardized spring ichthyoplankton density, log-transformed	1951-2018	4
Symbolophorus californiensis (bigfin lanternfish)	Standardized spring ichthyoplankton density, log-transformed	1951-2018	4
Tarletonbeania crenularis (blue lanternfish)	Standardized spring ichthyoplankton density, log-transformed	1951-2018	4
Triphoturus mexicanus (Mexican lampfish)	Standardized spring ichthyoplankton density, log-transformed	1951-2018	4
Vinciguerria spp. (Lightfishes)	Standardized spring ichthyoplankton density, log-transformed	1951-2018	4
Citharichthys sordidus (Pacific sanddab)	Standardized juvenile counts, log-transformed, core survey area	1990-2018	5
Citharichthys stigmaeus (speckled sanddab)	Standardized juvenile counts, log-transformed, core survey area	1990-2018	5
Doryteuthis opalescens (market squid)	Standardized counts, log-transformed, core survey area	1990-2018	5
Engraulis mordax (northern anchovy)	Standardized juvenile counts, log-transformed, core survey area	1990-2018	5
Euphausiacea (krill)	Standardized counts, log-transformed, core survey area	1990-2018	5
Merluccius productus (Pacific hake)	Standardized juvenile counts, log-transformed, core survey area	1990-2018	5
Sardinops sagax (Pacific sardine)	Standardized counts (juv & adult), log-transformed, core survey area	1990-2018	5
Sebastes entomelas (widow rockfish)	Standardized juvenile counts, log-transformed, core survey area	1990-2018	5
Sebastes goodei (chilipepper rocksfish)	Standardized juvenile counts, log-transformed, core survey area	1990-2018	5
Sebastes jordani (shortbelly rockfish)	Standardized juvenile counts, log-transformed, core survey area	1990-2018	5
Sebastes mystinus (blue rockfish)	Standardized juvenile counts, log-transformed, core survey area	1990-2018	5
Sebastes paucispinis (bocaccio rockfish)	Standardized juvenile counts, log-transformed, core survey area	1990-2018	5
Sebastes semicinctus (halfbanded rockfish)	Standardized juvenile counts, log-transformed, core survey area	1990-2018	5

[1]UCSC ROMS model, [2]NOAA Marine Mammal Lab, [3]Point Blue / USFW, [4]CalCOFI, [5]NOAA Rockfish Recruitment & Ecosystem Assessment Survey

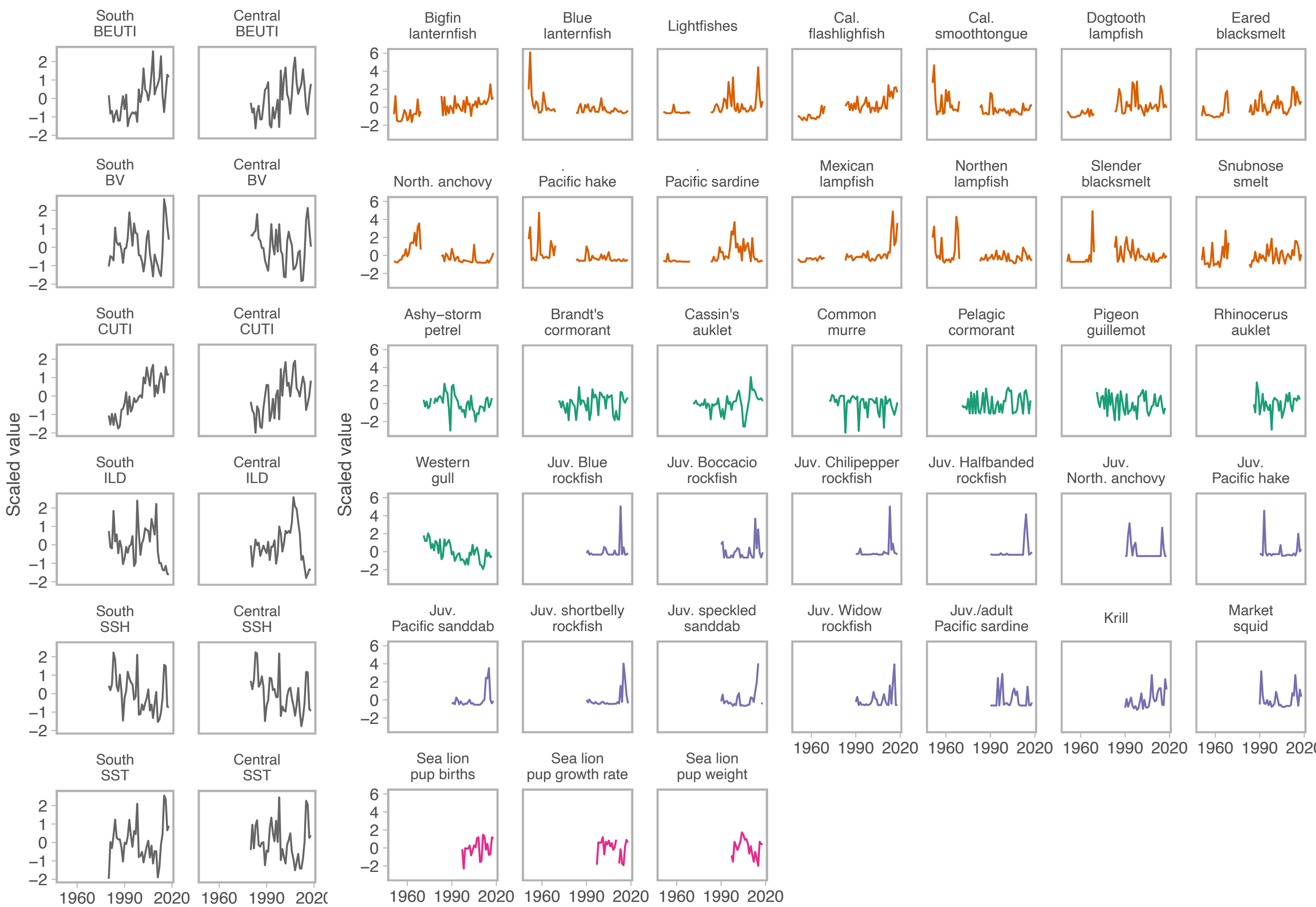
S2 Table. Summary information for the Bayesian DFA biology-covariate one-trend candidate models and the top two biology only models (years 1981-2017). Only one trends models are shown because they outperformed all two and three trend models. The table indicates whether process error was estimated, the number of model trends, estimated log predicted densities (ELPD), standard error of ELPD, and the environmental covariate included in model. All models had an AR(1) coefficient on the trend and Student-t deviations. BEUTI = Biologically Effective Upwelling Transport Index; CUTI = Coastal Upwelling Transport Index; ILD = Isothermal Layer Depth; SST = Sea Surface Temperature; BV = Brunt-Väisälä frequency; SSH = Sea Surface Height.

Model	Process sigma	Variance index	Trends	ELPD	SE ELPD	Covariate	Region
1	**No**	**survey**	**1**	**-1878.71**	**71.52**	**BEUTI**	**Central**
2	No	survey	1	-1886.35	76.85	BEUTI	South
3	No	survey	1	-1905.27	81.98	CUTI	Central
4	No	survey	1	-1906.26	110.45	CUTI	South
5	Yes	survey	1	-1913.61	103.29	CUTI	South
6	No	survey	1	-1914.62	83.22	ILD	South
7	No	survey	1	-1925.76	91.42	ILD	Central
8	No	survey	1	-1927.33	88.26	SST	South
9	No	survey	1	-1928.03	88.39	BV	South
10	No	survey	1	-1928.63	80.97	SST	Central
11	No	survey	1	-1934.49	81.35	BV	Central
12	Yes	survey	1	-1936.40	92.00	ILD	Central
13	No	survey	1	-1946.75	86.33	SSH	South
14	**No**	**survey**	**1**	**-1951.44**	**73.59**	**No covariate**	**Central**
15	Yes	survey	1	-1959.39	93.68	BV	Central
16	Yes	survey	1	-1966.10	106.22	SST	South
17	Yes	survey	1	-1966.70	85.47	ILD	South
18	Yes	survey	1	-1970.95	86.87	BV	South
19	Yes	survey	1	-1981.83	88.03	BEUTI	Central
20	No	survey	1	-1987.54	75.31	SSH	Central
21	Yes	survey	1	-1987.81	89.00	CUTI	Central
22	Yes	survey	1	-1993.32	92.03	BEUTI	South
23	Yes	survey	1	-1998.69	90.78	SSH	South
24	Yes	survey	1	-2005.40	77.06	SST	Central
25	**Yes**	**survey**	**1**	**-2038.71**	**91.44**	**No covariate**	**Central**
26	Yes	survey	1	-2067.22	97.04	SSH	Central

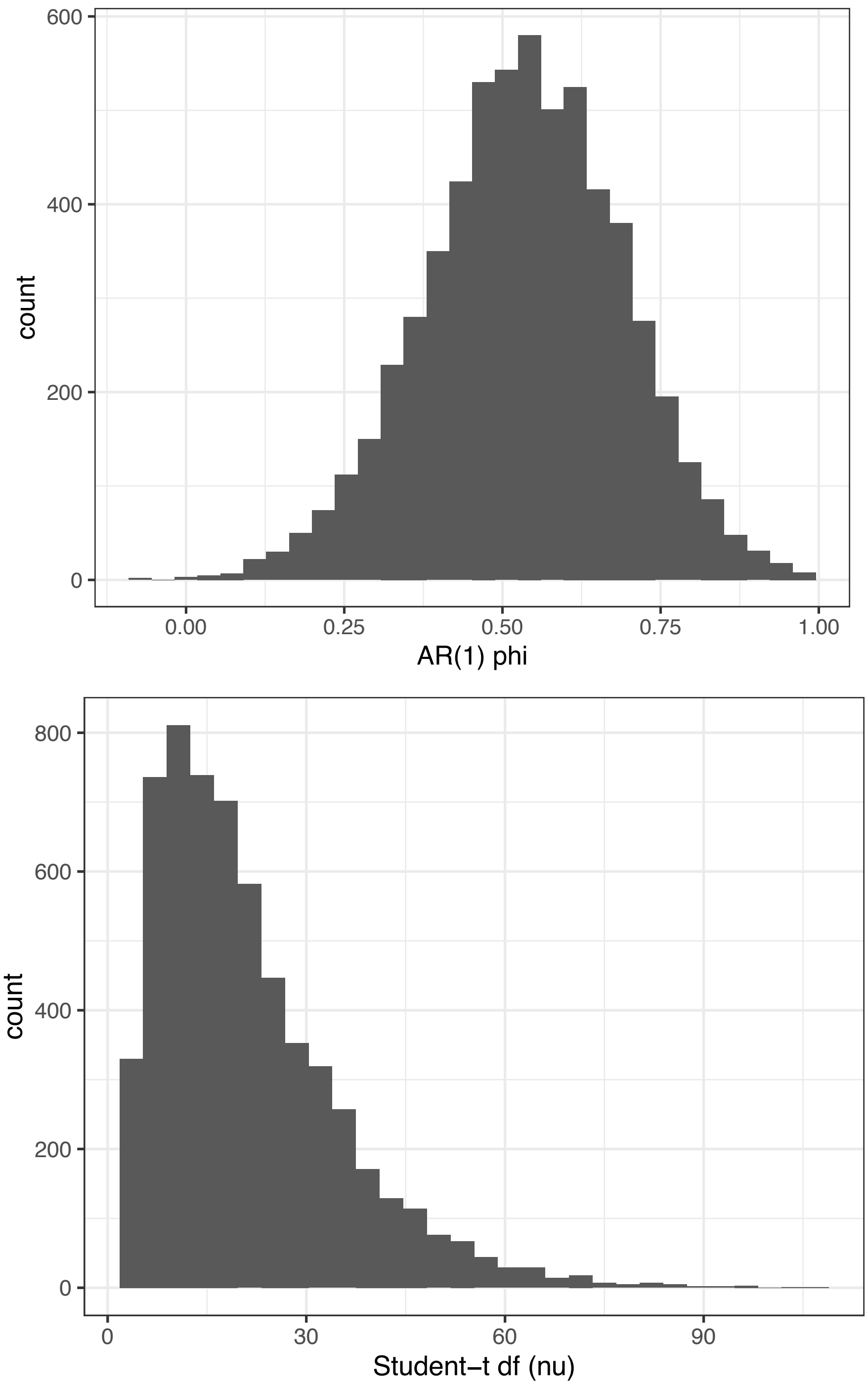
S3 Table. Observations, predictions, and prediction errors for single species parameters in 2018. The predictions and error were derived from the top four biology-covariate models shown in Table 2. Species with the lowest predictions are highlighted in bold.

Time series	BEUTI			CUTI			SST			ILD		
	Pred.	Observed	Pred. error	Pred.	Observed	Pred. error	Pred.	Observed	Pred. error	Pred.	Observed	Pred. error
Juv. Pacific sanddab	0.512	0.506	**0.000**	0.558	0.506	**0.003**	0.487	0.506	**0.000**	0.414	0.506	**0.008**
Juv. halfbanded rockfish	-0.087	0.008	**0.009**	-0.075	0.008	**0.007**	-0.069	0.008	**0.006**	-0.073	0.008	**0.007**
Blue lanternfish	0.277	0.157	**0.014**	0.211	0.157	**0.003**	0.149	0.157	**0.000**	0.176	0.157	**0.000**
Slender blacksmelt	-0.121	0.004	**0.016**	-0.104	0.004	**0.011**	-0.005	0.004	**0.000**	-0.029	0.004	**0.001**
Common murre	0.355	0.226	**0.017**	0.302	0.202	**0.010**	0.171	0.202	**0.001**	0.197	0.202	**0.000**
Snubnose smelt	0.188	0.381	**0.037**	0.237	0.381	**0.021**	0.227	0.381	**0.023**	0.203	0.381	**0.032**
Market squid	0.561	0.799	**0.056**	0.560	0.799	**0.057**	0.471	0.799	**0.107**	0.418	0.799	**0.145**
Juv./adult Pacific sardine	-0.483	-0.242	**0.058**	-0.466	-0.242	**0.050**	-0.287	-0.242	**0.002**	-0.311	-0.242	**0.005**
Dogtooth lampfish	0.081	-0.184	**0.071**	0.127	-0.184	0.097	0.197	-0.184	0.146	0.161	-0.184	**0.119**
Cassin's auklet	0.526	0.246	**0.078**	0.496	0.260	**0.055**	0.381	0.260	**0.014**	0.396	0.260	**0.018**
Eared blacksmelt	0.405	0.708	0.092	0.424	0.708	**0.080**	0.329	0.708	**0.143**	0.288	0.708	0.176
Brandt's cormorant	0.221	0.545	0.105	0.216	0.545	0.109	0.136	0.545	0.168	0.109	0.545	0.190
Larv. Pacific hake	-0.067	-0.467	0.160	-0.047	-0.467	0.176	-0.073	-0.467	0.155	-0.079	-0.467	0.150
Juv. speckled sanddab	0.657	0.061	0.355	0.659	0.061	0.357	0.551	0.061	0.240	0.517	0.061	0.208
Juv. Pacific hake	0.398	0.998	0.360	0.453	0.998	0.298	0.393	0.998	0.367	0.350	0.998	0.421
Krill	0.438	1.062	0.389	0.366	1.062	0.484	0.230	1.062	0.691	0.259	1.062	0.644
Juv. shortbelly rockfish	0.469	-0.171	0.409	0.527	-0.171	0.488	0.502	-0.171	0.453	0.401	-0.171	0.328
Juv. blue rockfish	0.138	-0.536	0.453	0.091	-0.536	0.392	0.014	-0.536	0.302	0.061	-0.536	0.355
Sea lion pup weight	-0.227	0.467	0.482	-0.225	0.467	0.479	-0.257	0.467	0.525	-0.210	0.467	0.459
Sea lion pup births	0.195	0.961	0.586	0.126	0.961	0.697	0.024	0.961	0.878	0.005	0.961	0.912
Lightfishes	0.017	0.800	0.613	0.127	0.800	0.453	0.220	0.800	0.337	0.160	0.800	0.409
Juv. boccacio rockfish	0.265	-0.522	0.619	0.199	-0.522	0.519	0.101	-0.522	0.387	0.182	-0.522	0.496
Cal. smoothtongue	0.129	0.977	0.719	0.139	0.977	0.703	0.125	0.977	0.727	0.067	0.977	0.828
Sea lion pup growth	-0.264	0.612	0.767	-0.264	0.612	0.768	-0.210	0.612	0.676	-0.175	0.612	0.619
Bigfin lanternfish	0.075	0.959	0.780	0.089	0.959	0.757	0.109	0.959	0.721	0.086	0.959	0.761
Larv. Pacific sardine	-0.208	-1.104	0.802	-0.286	-1.104	0.668	-0.357	-1.104	0.557	-0.269	-1.104	0.697
Cal. flashlighfish	0.430	1.383	0.908	0.406	1.383	0.954	0.323	1.383	1.125	0.274	1.383	1.229
Northen lampfish	0.480	-0.756	1.529	0.459	-0.756	1.475	0.373	-0.756	1.274	0.340	-0.756	1.202
Larv. northern anchovy	-0.337	1.090	2.039	-0.257	1.090	1.815	-0.119	1.090	1.462	-0.195	1.090	1.654
Juv. widow rockfish	0.299	-1.374	2.798	0.292	-1.374	2.774	0.199	-1.374	2.475	0.228	-1.374	2.567
Mexican lampfish	0.249	2.233	3.934	0.299	2.233	3.740	0.322	2.233	3.652	0.246	2.233	3.947
Juv. chilipepper rockfish	0.298	-1.771	4.280	0.311	-1.771	4.337	0.256	-1.771	4.111	0.308	-1.771	4.321
Juv. northern anchovy	0.010	NA	NA	0.207	NA	NA	0.269	NA	NA	0.217	NA	NA
Ashey-storm petrel"	0.158	NA	NA	0.218	NA	NA	0.195	NA	NA	0.118	NA	NA
Pelagic cormorant	0.518	NA	NA	0.479	NA	NA	0.352	NA	NA	0.371	NA	NA
Pigeon guillemot	0.507	NA	NA	0.463	NA	NA	0.303	NA	NA	0.329	NA	NA
Rhinocerus auklet	0.356	NA	NA	0.292	NA	NA	0.185	NA	NA	0.192	NA	NA
Western gull	-0.064	NA	NA	-0.074	NA	NA	-0.026	NA	NA	-0.048	NA	NA

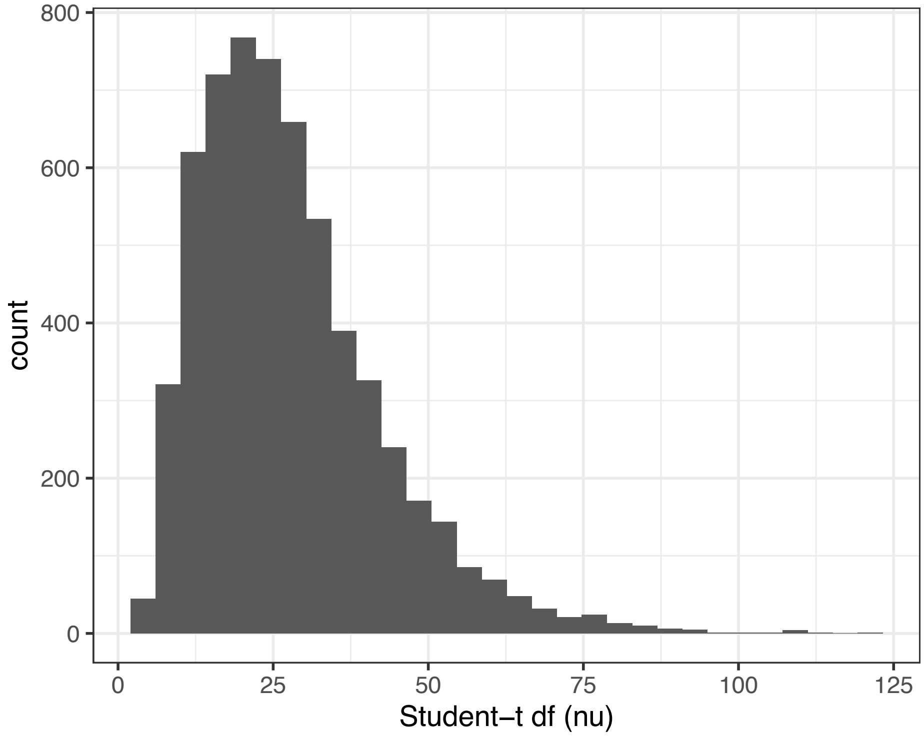
S1 Figure. Climate and biology time series used in the study analyses. They include climate indices (gray), ichthyoplankton abundance indices (orange), seabird reproductive success (teal), juvenile fishes and invertebrates (blue), and California sea lion pup parameters. Time series are scaled by their mean and standard deviation.



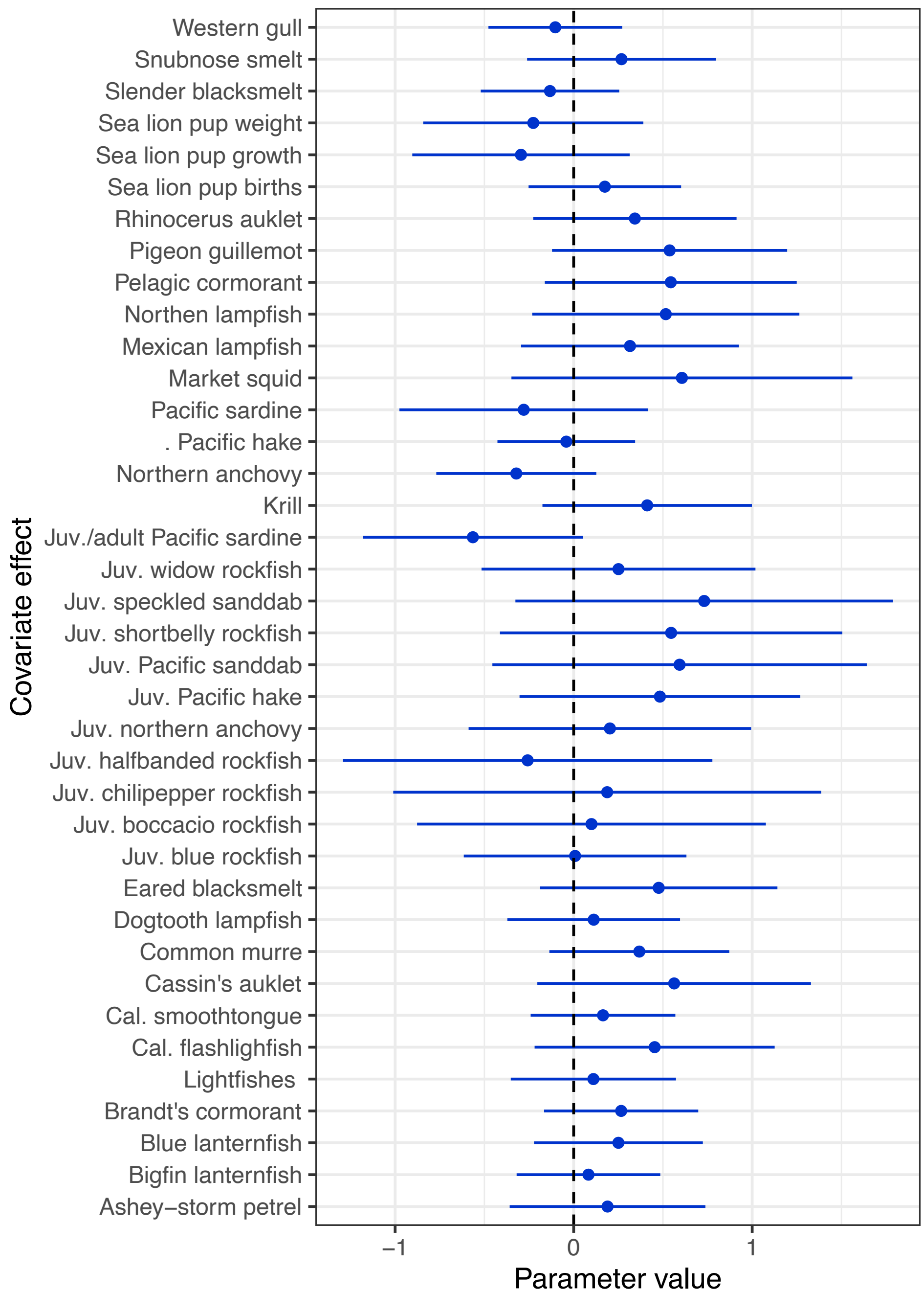
S2 Figure. AR(1) coefficient on the southern/central California latent climate trend (top) and support for a heavy-tailed deviations of the latent trend (bottom). Smaller values of the degrees of freedom parameter (e.g., less than 10 or 20) are consistent with heavy-tailed deviations.



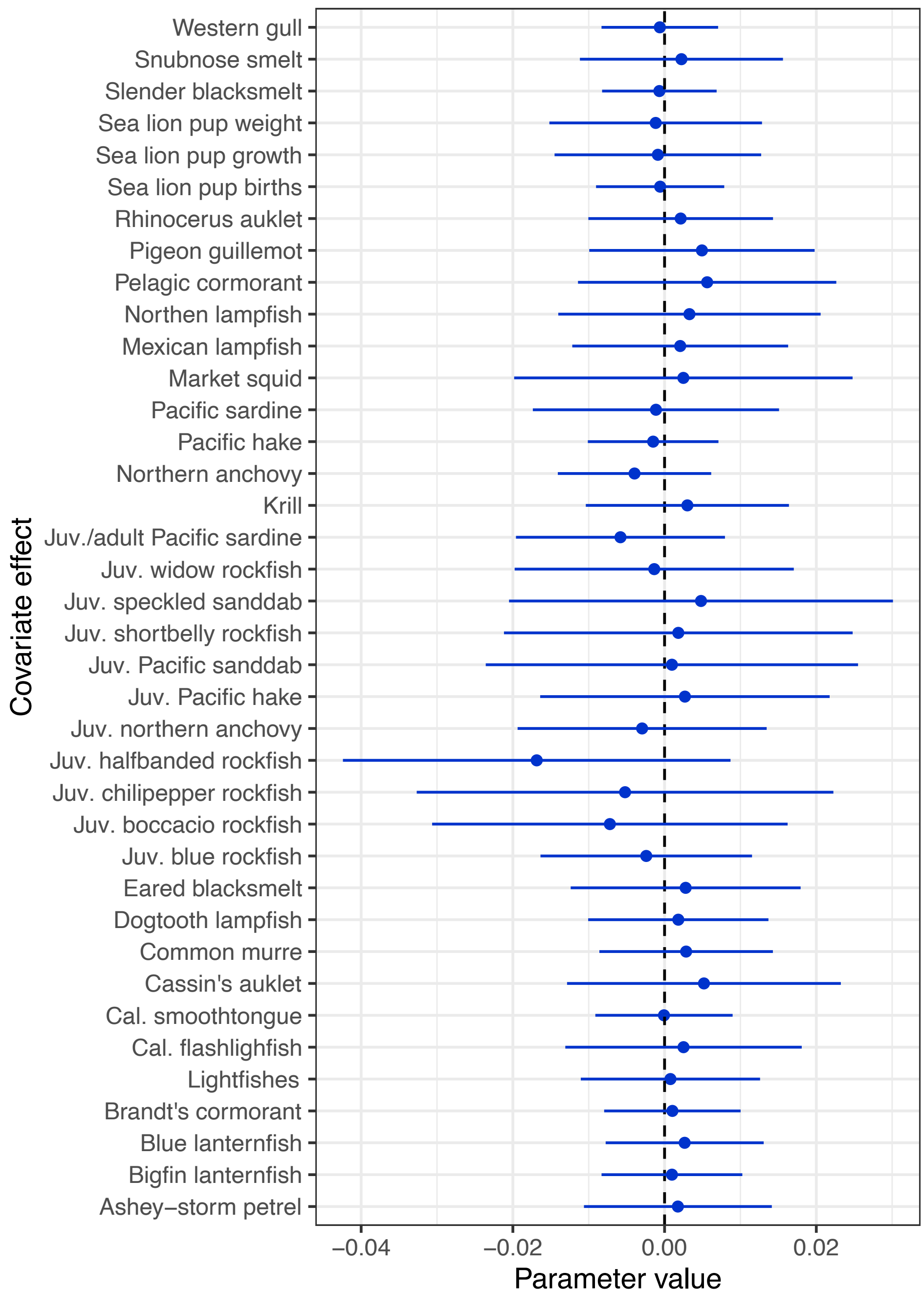
S3 Figure. The Student-t deviations degrees of freedom parameter (nu) in the southern/central California biology trend.



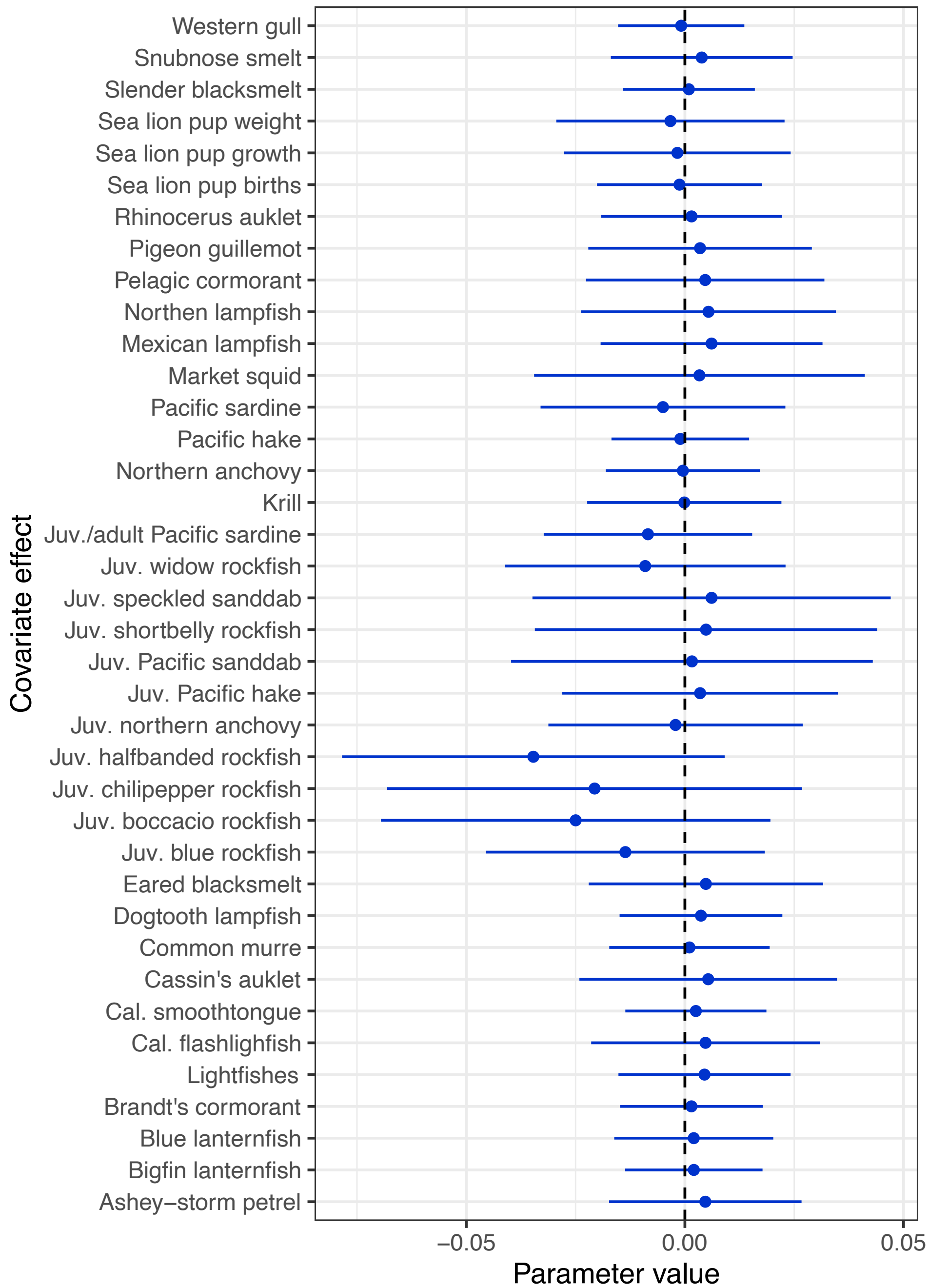
S4 Figure. A summary of the effect of the Cumulative Upwelling Transport Index (CUTI) on the individual single species parameter included in the DFA analyses. Cal. = California, Juv. = juvenile fish stage, Larv. = larval fish stage, Juv./adult = juvenile and adult stages combined, all other fish are larval fish. Blue error bars reflect 95% credible intervals.



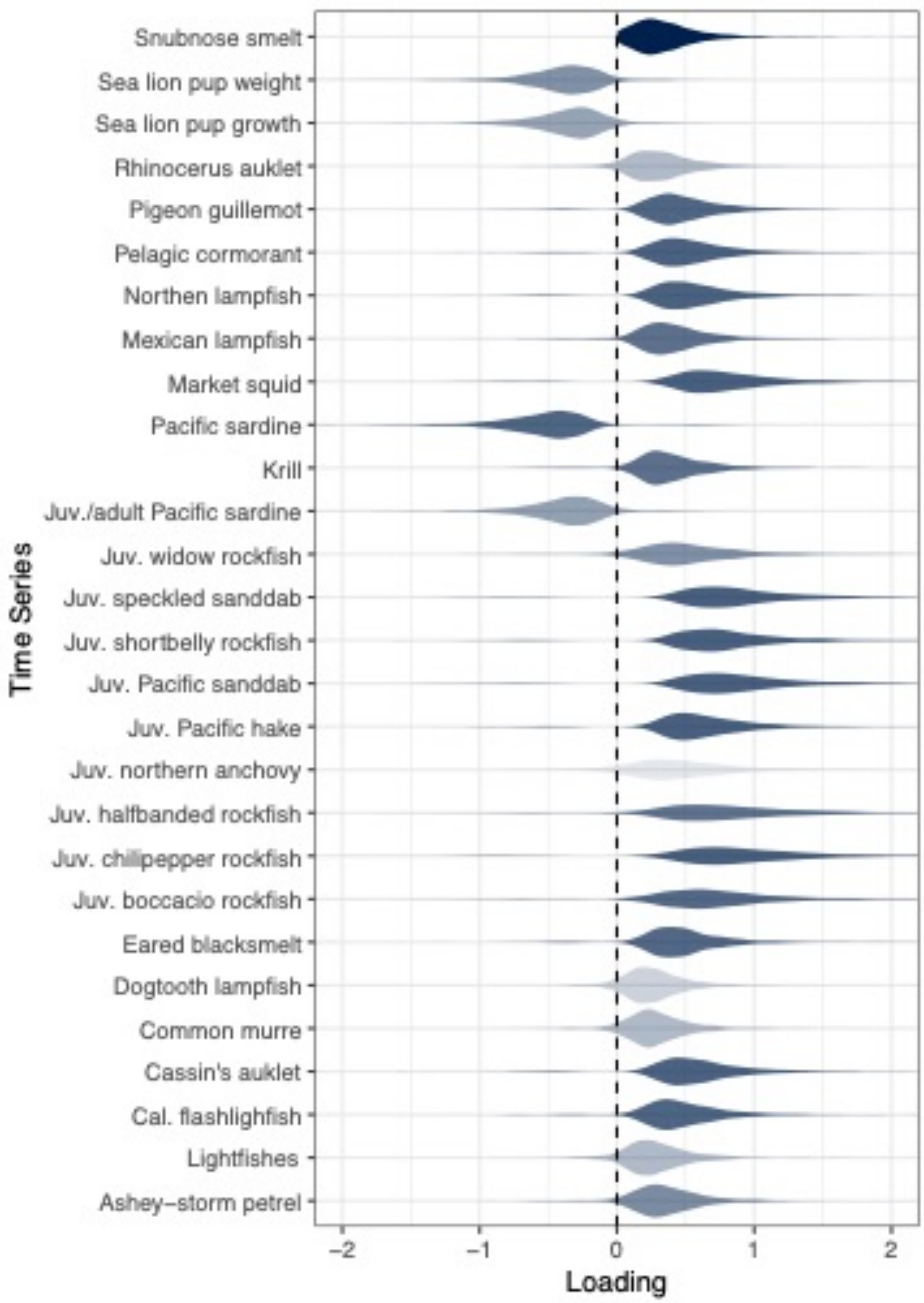
S5 Figure. A summary of the effect of the Isothermal Layer Depth (ILD) on the individual single species parameter included in the DFA analyses. Cal. = California, Juv. = juvenile fish stage, Larv. = larval fish stage, Juv./adult = juvenile and adult stages combined, all other fish are larval fish. Blue error bars reflect 95% credible intervals.



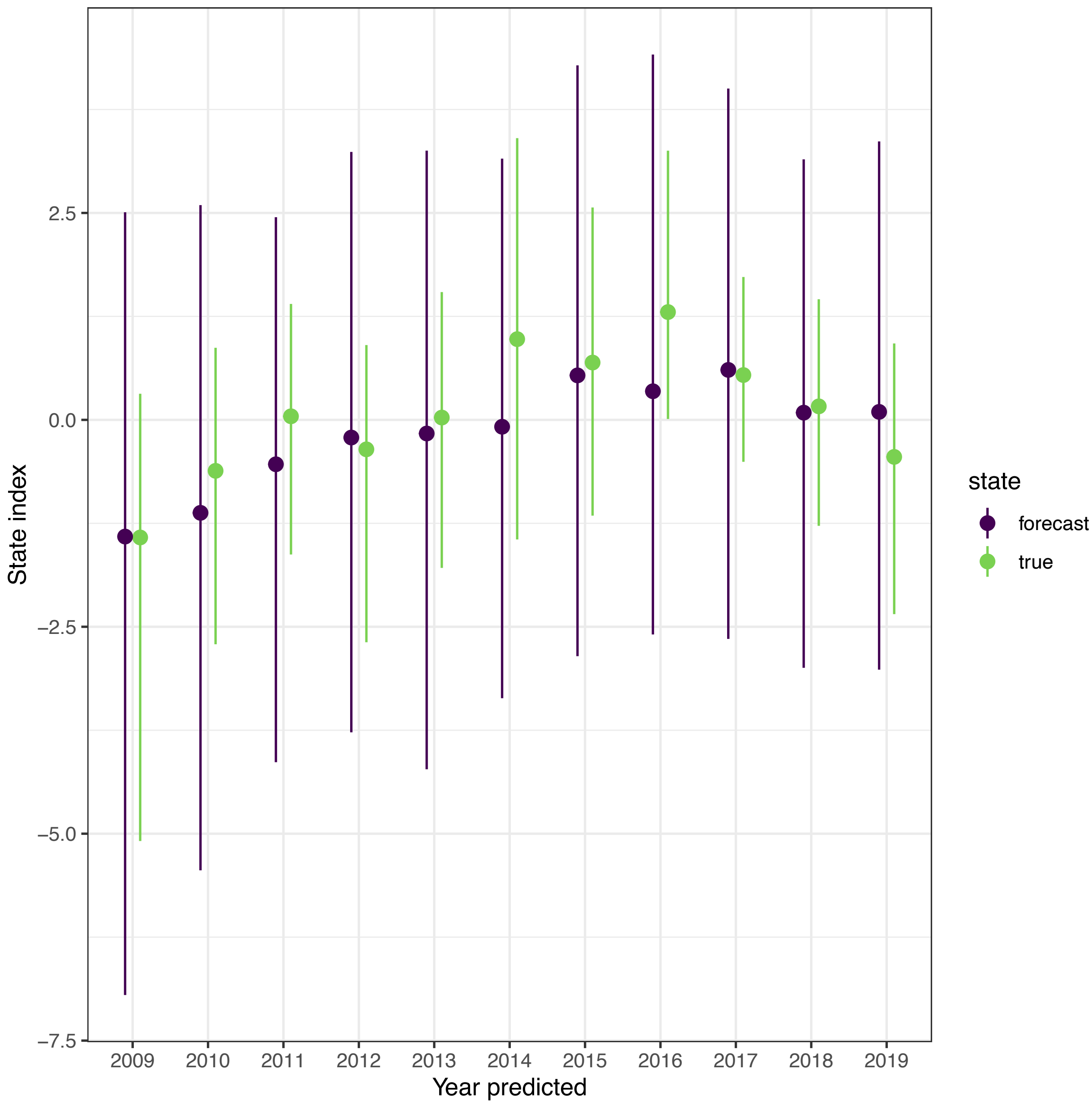
S6 Figure. A summary of the effect of the sea surface temperature on the individual single species parameter included in the DFA analyses. Cal. = California, Juv. = juvenile fish stage, Larv. = larval fish stage, Juv./adult = juvenile and adult stages combined, all other fish are larval fish. Blue error bars reflect 95% credible intervals.



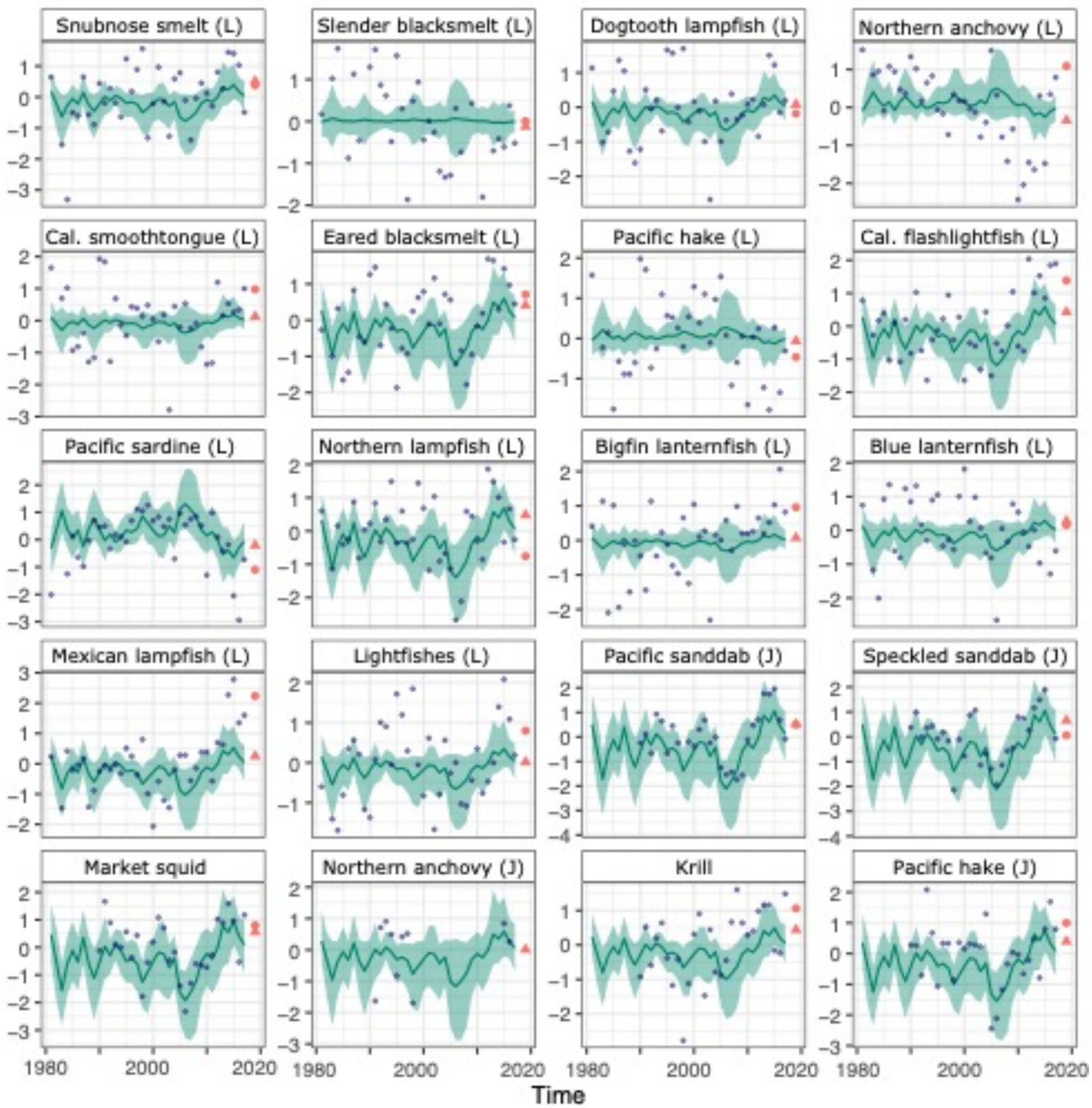
S7 Figure. Community variability in the southern California Current ecosystem (1981-2018). See Fig. 6 for shared trend and below for posterior distributions for loadings on individual time series. Only time series with ≥ 90% of loading distributions above or below zero are shown. Loadings with darker shading indicate time series loading most strongly on the biology trend. See Table S1 for times series details.



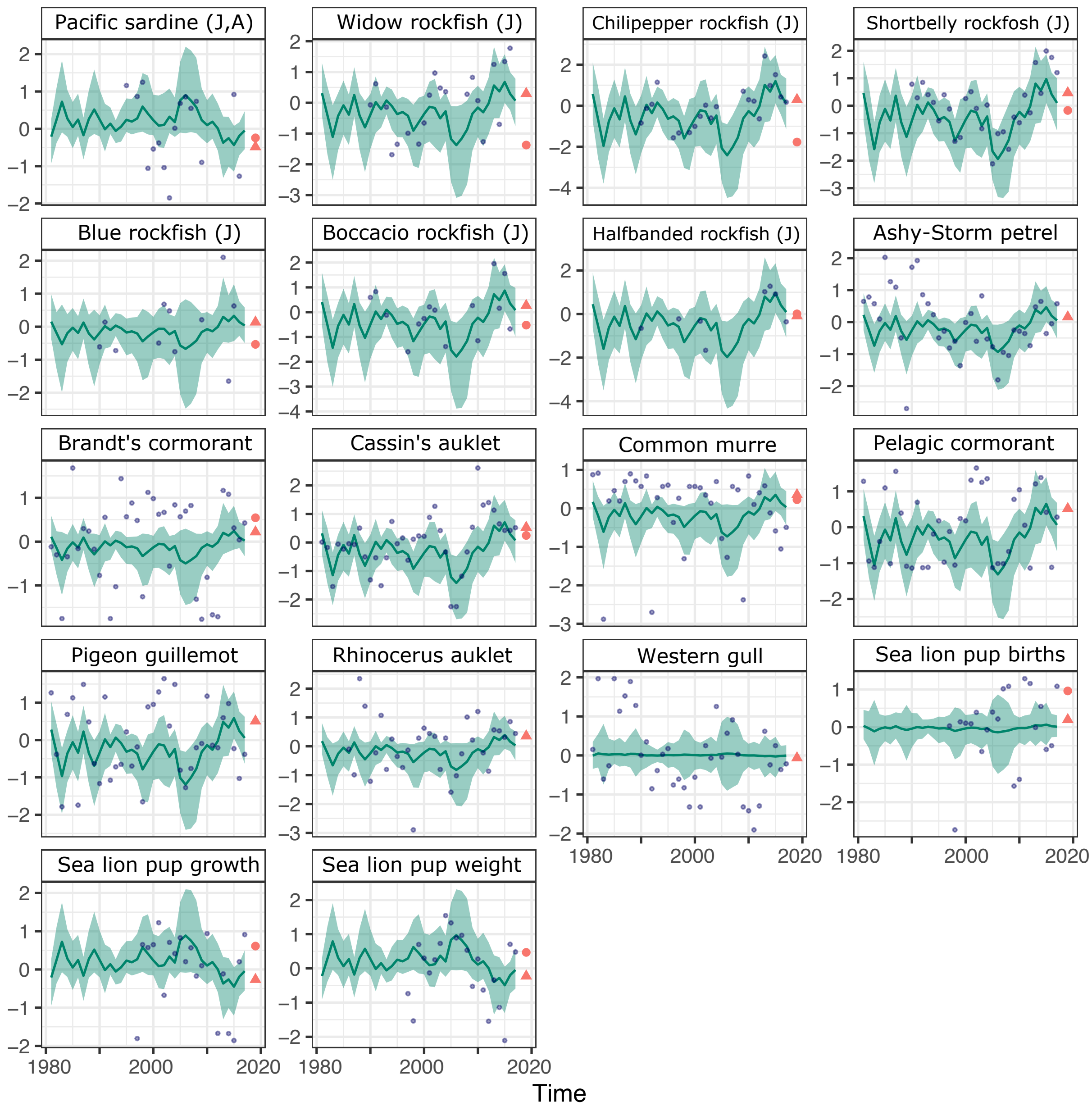
S8 Figure. Forecasts and model estimates of the ‘true’ community state in the southern and central California Current in years 2009—2018 (circle, with 95% credible intervals).



S9 Figure. Fitted values for biology-covariate model including BEUTI (nitrate flux) as a covariate (1981-2017). Blue circles = observations; blue line = fitted model, red circles = 2018 observations; red triangles = model predictions of single species parameters in 2018. Fish life stages: L = larval, J = juvenile, A = adult. 2018 observations were not available for juvenile northern anchovy.



S9 Figure cont. Fitted values for SCC biology model including BEUTI (nitrate flux) as a covariate (1981-2017). Blue circles = observations; blue line = fitted model; red circles = 2018 observations; red triangles = model predictions of single species parameters in 2018. Fish life stages: L = larval, J = juvenile, A = adult. 2018 seabird observations were only available for Brandt's cormorant, Cassin's auklet, and Common murre.



S10 Figure. Log coefficient of variation (CV) of 2018 predictions of individual species parameters plotted against (a, b) the mean and log CV of loadings related to each species, and (c, d) the mean and log CV of coefficients relating each species to BEUTI (nitrate flux). Model loadings, coefficients and predictions were derived from Model 1 listed in Table 2.